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"Accumulation of the Planets"

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The purpose of this project is to increase understanding of planet forming processes that are likely to have occurred in the Solar System during its early evolution. This was accomplished by development of computer models that are compatible with the present state of the Solar System as well as with observational and theoretical data attained from astrophysical observations and theory.

The principal achievements of this program are:

(A) Completion of the first fully three-dimensional numerical calculation using numerical integration of the growth of terrestrial (inner) planets in our Solar System (Chambers and Wetherill, 1998). This confirms earlier less rigorous studies by showing that the outcome of this process is highly chaotic. A wide range of planetary formations can occur, and the details of our Solar System are just one out of many others that could have occurred under even nearly identical conditions. The most common outcome is found to be two large planets, "Earth" and "Venus" in this region of the Solar System, but some other aspects of the calculated orbits indicate that the model is oversimplified, as would be expected for the first investigation of this kind. This theoretical work is being pursued by Dr. Chambers at the NASA Ames research center, with NASA funding.

(B) The first three-dimensional numerical integration model of the formation of planetary bodies in the asteroid region between Mars and Jupiter (Chambers and Wetherill, 2001; Meteoritics and Planetary Science, 36, 381-399). If it is assumed that the disk of dust and gas, from which the planets formed, varied smoothly with distance from the Sun, it is found that instead of only small asteroids, such as those observed, both planetary and asteroid size bodies are formed. However, following the subsequent formation of the giant planets Jupiter and Saturn the gravitational perturbations of these planets will cause the large "asteroid belt" planets to be removed from the Solar System, leaving behind only small bodies comparable in size and number of the present small asteroids.

(C) More extensive and rigorous development of the "standard model" for planetary formation in order to permit a more accretion consideration of its validity.

During the past decade, the efforts of workers in this field have succeeded in developing a shared understanding of models for the formation of the inner planets (Mercury to Mars) and for the "giant" planets Jupiter and Saturn. More recently, the results of the discovery of giant planets orbiting other stars have challenged aspects of the validity of the standard model. We have addressed this situation two ways:

(1) Development of more rigorous dynamic models within the framework of the standard model, in order to distinguish between discrepancies that are the result of insufficient development of details in the present computational approach and

(2) Those that are a consequence of more basic differences between the assumptions of the standard model and the actual nature of the planetary formation processes themselves.

In this report we emphasize our contribution to item (1). A parallel study, rather more directed to item (2) has been described in another report that discusses our work in the program "Origins of Solar Systems," NAG5-6977.

A major portion of the results that fall into the category of item (1) were carried out by postdoctoral investigators Satoshi Inaba and Steven Kortenkamp and the PI. The first of these contributions consisted of an extension of Inaba's doctoral thesis at the Tokyo Institute of Technology. This represents an improved statistical method for the calculations of planetary accumulations using the currently standard model of terrestrial planet formation and the latest results of planetary dynamic theory (Inaba et al., 2000). This includes a thorough and satisfactory understanding of the differences of this work and those available earlier (eg. Wetherill and Stewart, 1992).

Subsequently, Inaba and the Principal Investigator carried out the first calculations of the growth of the dense inner core of Jupiter and Saturn that are consistent with the assumptions of the standard model. This has been submitted and reviewed for publication. Inaba has recently returned to Japan and we are making final changes on this manuscript.

In addition, Wetherill and Inaba have addressed other aspects of the standard model in a publication, "Planetary Accumulation with a Continuous Supply of Planetesimals", included in the references listed below (2000).

References

Chambers, J.E. and G.W. Wetherill, Making the terrestrial planets: N – body integrations of planetary embryos in three dimensions, *Icarus, 136*, 304-327, 1998.

Chambers, J.E. and G.W. Wetherill, Planets in the asteroid belt, *Meteoritics and Planetary Science 36*, 381-389, 2001.

Inaba, S., H. Tanaka, K. Nakazawa, G.W. Wetherill, and E. Kokubo, High-accuracy statistical simulation of planetary accretion: II. Comparison With N- body Simulation, *Icarus, 149,* 235-250, 2001.

Inaba, S. and G.W. Wetherill, Formation of gas giant planets: Core accretion models with fragmentation, submitted to *Icarus* 2001.

Wetherill, G.W. and S. Inaba, Planetary accumulation with a continuous supply of planetesimals, *Space Science Review, 92*, 311-320, 2000.